SIMULATION MODEL TO EVALUATE MAINTENANCE STRATEGIES FOR LARGE NETWORK OF FIELDED SYSTEMS*

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Abstract A dynamic simulation model of a field maintenance organization has been developed and validated. The objective of the model is to provide an analytical tool for evaluating the operational feasibility of new maintenance strategies prior to their introduction into the field. This simulation model is an accurate replica of the policies and time critical maintenance activities within a field organization, providing a rendering in detail of each technician and each facility as events take place in time. This paper discusses the structure of the model, the functions simulated, the validation experiment, and an application of the model.

INTRODUCTION

The Federal Aviation Administration (FAA) operates and maintains an extensive network of air navigation, communications, and air traffic control facilities of the National Airspace System. The FAA maintenance organization for serving these fielded facilities is divided geographically into eleven regions, nine of which are conterminous. Each conterminous regional organization is further partitioned into approximately ten sectors. The sector is the basic maintenance field organization since the maintenance responsibilities and activities are confined within its boundary. Each sector contains about 50-120 technicians serving the 150 or more facilities. To provide the high degree of system availability to the aviation users, these fielded systems require frequent technician preventive maintenance (PM) visits. The high PM workload and the minimization of the outage restoration time have led to the establishment of sector maintenance organization wherein technicians work stations are located in close proximity to the facility locations.

The FAA is actively pursuing the replacement of the presently fielded equipments with modernized equipment, as well as the introduction of more systems into field. To exploit the maintenance productivity benefits of the modernized equipments while preserving the present level of system performance, new maintenance strategies are under consideration by the

* This paper is based upon maintenance organization studies performed by MITRE for the Airway Facilities Service, Federal Aviation Administration under Contract No. DOT-FA80WA-4370. The contents of this paper reflect the views of The MITRE Corporation, which is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of the FAA.

FAA. These maintenance concepts may include the reduction of PM visits, the implementation of Remote Maintenance Monitoring (RMM), the consolidation of technician work stations, the training of highly specialized technicians, or the combination of these concepts. However, a question arises as to whether these maintenance concepts would be operationally feasible in the field. That is, will the implementation of these concepts in the field provide satisfactory system performance to the aviation users in terms of outages and restoration time without increasing substantially the workload of the individual field technicians?

A simulation model of a representative field sector organization has been developed to provide to the FAA a management tool for evaluating the operational feasibility of new maintenance strategies. This model has been validated by a field test and applied (Reference 1,2). This paper describes the rationale for using the simulation technique, the conceptual formulation of the model, the validation methodology, and a particular application of this model.

RATIONALE FOR UTILIZING SIMULATION TECHNIQUES

The analysis of new maintenance concepts does not lend itself to conventional mathematical techniques because the sector structure and the decision logic for utilizing the technicians are rather complex. For example, the sector usually contains a variety of systems at many diverse locations. Furthermore, the technicians are usually certified for more than one system. In addition, the maintenance resource of the sectors, namely the number of technicians, is time-varying due to technician training, unscheduled and scheduled absences, etc. Thus, it can be seen that a conventional mathematical model (e.g., queueing model) describing this situation in detail would have to make many simplifying assumptions which would limit its usefulness.

Simulation provides the required detail, since it imitates all the sector's daily operations and interactions on a person-by-person and an event-by-event basis, as if the new concept was actually implemented. The time critical workload of the technicians such as travel, corrective maintenance (CM), and preventive maintenance are accounted for in detail in the simulation. The simulation approach has the additional value of allowing the active participation of the sector management in dealing with the organizational details necessary for implementation.

FORMULATION OF THE SIMULATION MODEL

The construction of a computer model of a physical system requires, first, an analysis of the complex details of the modeled system and then the extraction of the salient, interacting elements of the modeled system that contribute heavily to the outputs of the model.

There are two main measures used to assess the operational feasibility of a maintenance strategy; namely, average time to restore a facility outage and the time critical workload of the technicians. Therefore, these two measures are also part of the model outputs. The time to restore reflects the amount of time elapsed from the instant the system has failed to the time the failed unit has been repaired. Therefore, this time interval includes the time it takes to find an available technician and the time it takes for travel, trouble-shoot, and repair. The time critical workload measures the amount of time a technician spends on travel, PM, and CM, relative to his total working time. That is:

$$\text{Time Critical Workload} = \frac{(\text{Travel time} + \text{PM time} + \text{CM time})}{\text{Total working time}} \times 100\%$$

At the present time, the average time critical workload for the technician is approximately 50%. The other half of a technician's working time is allocated for other required activities such as training, documentation, vacations, and sick leaves.

After an in-depth interview with the sector management and field technicians, the following four essential elements of the field maintenance system have been identified:

1. The maintenance requirements, PM and CM, of the individual facilities in the sector.

2. The maintenance resources of the sector; namely, the technicians.

3. The sector's procedure for assigning technicians to perform PM and CM under a variety of staffing and restoration level conditions.

4. The dynamic movements and actions of the technicians on a daily basis (travel, PM and CM hands-on service time).

The PM and the CM requirements of the individual facilities are the driving force that triggers the responses of the sector's technicians. The third element alone forms the decision logic of the simulation model. The fourth element accounts for the dynamic nature of the model since each one of the maintenance activities (travel, PM, CM) consumes a finite amount of time. There are also secondary elements such as technician leave due to sickness, vacation, and training, and the availability of parts at the facility for CM. However, the effect of these elements is to modify (lengthen or delay) the dynamic movements and actions of the technicians.

Thus, one can conceptually visualize the sector as a system in which the regularly scheduled PMs of the facilities place a daily demand for services upon the technicians. This demand is deterministic in a typical sector, since PMs are scheduled in advance. The sector management responds to this demand by assigning the appropriate technicians to these tasks. This assignment policy is a function of the certification, availability, and the duty location of the technicians. The result of the PM job assignment process is a PM task queue (list of PMs to be performed) for each technician on each working day. The length of the PM queue for each technician varies from day-to-day and some of the PM tasks may require more than one technician. A technician normally discharges his maintenance responsibilities by traveling to the appropriate facilities and spending time on PM. However, if an outage or failure occurs during the regular working hours, his PM related activities or PM job queue may be interrupted and delayed if he is the best candidate for responding to this CM event. For off-hour outages of facilities, the sector has a different procedure for selecting technicians for callback repairs.

Conceptually, the sector is essentially a multi-queue (PM queues) system. The random CM events, relatively small in comparison with PM events, can be viewed as interruptions to the queues. The number of PM queues in the system is equal to the number of technicians in the sector.

THE SIMULATION MODEL

This section discusses the structure of the model, the functions simulated by the model and the model outputs. The model was programmed in GPSS and PL/I languages.

The sector model consists of three primary modules that simulate the maintenance activities and policies of the sector organization. The three modules are: sector data base, the corrective maintenance module, and the preventive maintenance module. The interaction between these modules is depicted in Figure 1.

SECTOR DATA BASE

Central to the specific operation of the sector model is the sector data base. Part of the data base contains information that is inputted to the model and remains constant throughout the simulation. The other part contains information that is initialized at the beginning of the simulation and then updated throughout the simulation period. The bulk of the data was derived from actual sector operations as logged over a twenty-month period.

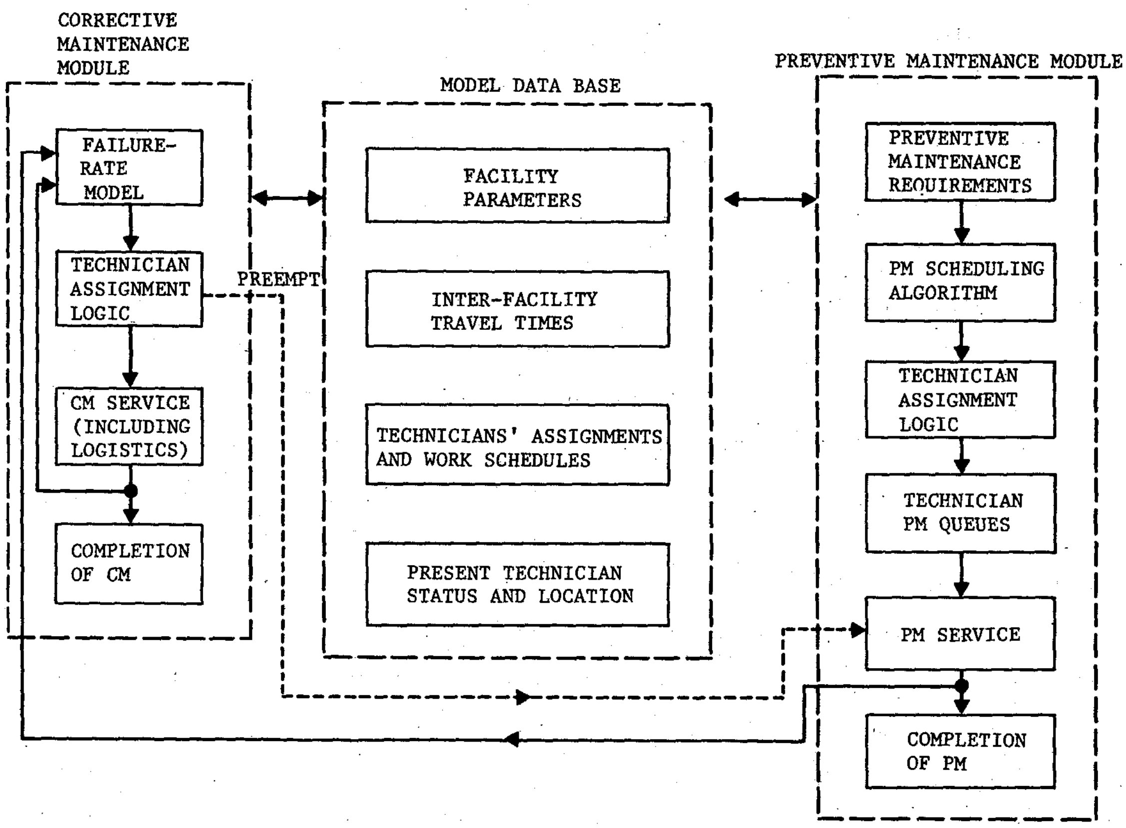

FIGURE 1
OVERVIEW OF SIMULATION MODEL

The sector data base is made up of four significant data blocks, the first being facility parameters. The facility parameters comprise a set of summary characteristics of each of the facilities. Specifically, the facility parameters include: the facility type, equipment redundancy, the preventive maintenance requirements, the mean-time-between-failures, mean troubleshoot time, mean repair time, probabliity of logistics delay, mean logistic delay, facility priority, facility restoration level, and any other information needed concerning the individual facilities. The facility parameters are inputted to the model and remain constant throughout the simulation period.

The second data block contains the location of each facility and the time to travel between any two facilities under normal and adverse weather conditions.

The third data block contains information on technician qualifications. This data block specifically includes assigned and alternate technicians for each facility, the technician call-back list for each facility, technician work schedule (i.e., days worked, which shift is worked), and information on technician leave (i.e., training, sick leave, vacation).

The fourth data block continually changes throughout the simulation period. This block keeps track of the location and job status (i.e., doing PM, doing CM, travel, etc.) of each of the technicians.

CORRECTIVE MAINTENANCE MODULE

The corrective maintenance module is responsible for the generation of failures at all facilities and the resulting actions necessary to repair the failure. The failure rate model determines the time of the failures at all facilities based on the mean-time-between-failures and the rate of visitations to the facility. The failure rate model receives data from the facility parameters data block and also from the PM modules. The technician assignment logic utilizes information from the sector data base to select a qualified and available technician to perform the corrective maintenance action. Since the CM has a higher priority, a PM task being performed by one technician may be pre-empted if no other available technicians can be found. This accounts for one of the interactions between the PM and CM modules. The CM service submodule carries out the actual CM action. This submodule travels the selected technician to the failed facility and allows the technician to troubleshoot and repair the facility, including any logistics action that may be required. The CM service submodule requires data from the facility parameters and facility locations data blocks.

Two types of facility failures are simulated in the failure rate model. The first kind is the random facility failure that cannot be prevented by site visitations of the technicians. They include facility failures due to weather effects, communication line failure, and other unscheduled failures.

The second type of failure is one that shows gradual equipment deterioration. Therefore, if a technician spots the impending failure during site visitation, the failure can be prevented. Equipments of the vacuum-tube technology often display this kind of failure characteristics. Since the simulation model might be used to evaluate the impact of varying the PM visitation rates to the facility, a mathematical model has been developed, Reference 3, and implemented into the simulation. The implementation of the 3-state, Markov model is shown in Figure 2. The zero state (S_0) is normal, i.e., there is no pending failure. The next state is the pending failure state (S_1), i.e., a pending failure can be spotted by a technician. The last state is the actual failure state (S_2). The state transitions normally occurs sequentially, from S_0 to S_1 to S_2. However, upon the detection of the pending failure state by a technician, the facility is **reinitialized** to S_0, the operating state.

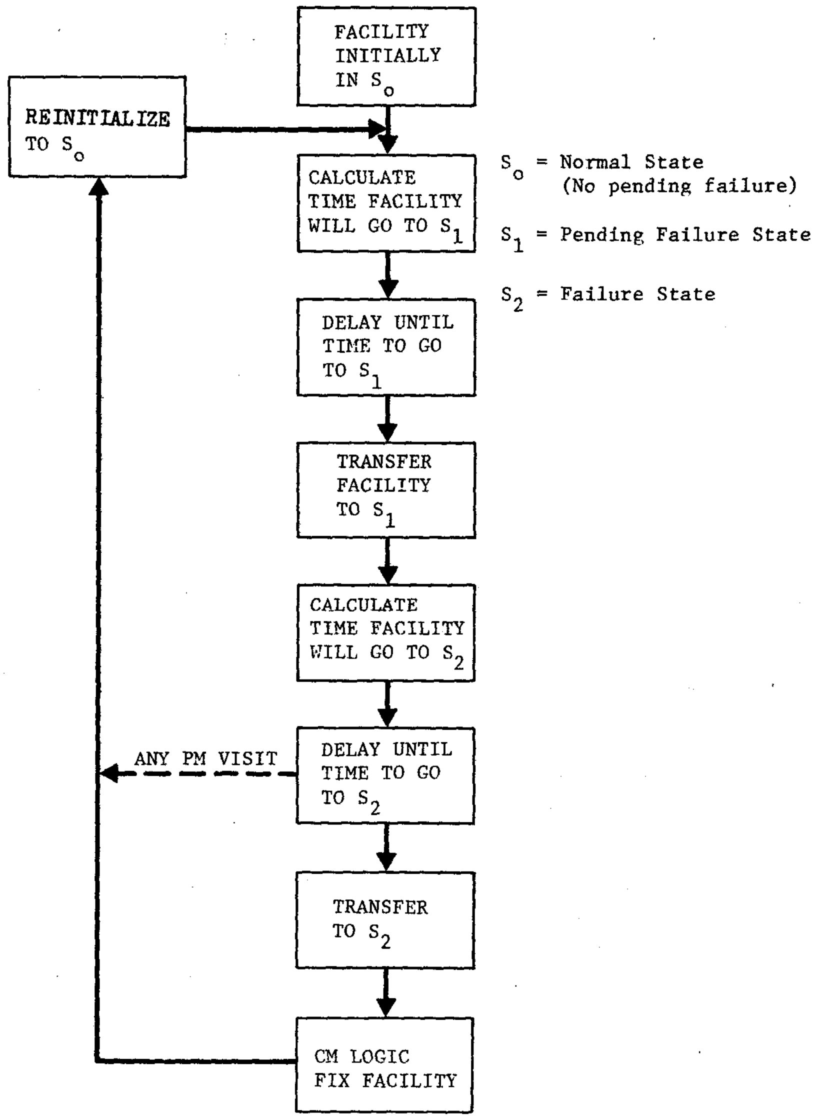

FIGURE 2
FAILURE RATE MODEL IMPLEMENTATION

PREVENTIVE MAINTENANCE MODULE

The preventive maintenance module is responsible for initiating and completing preventive maintenance events as specified by the PM requirements. The PM schedule is derived by an independent algorithm prior to the simulation period using a list of PM requirements for each facility as a basis. The PM scheduler utilizes such data as technician responsibilities and interfacility travel times to calculate an initial PM schedule for each day of the simulation period. The technican assignment logic uses the PM schedule as input in order to determine which technician will be assigned to specific PM events on a daily basis. An example of the PM technician assignment logic is given in Figure 3. The technician assignment logic is necessary in order to compensate for the inability to predict failures and therefore conflicting CM events. It is necessary to queue PM events as a function of technician assigned since each technician is normally responsible for more than one PM event per day. The PM service submodule carries out the travel and work actually associated with the preventive maintenance task. After a PM task is completed, this information is fed to the CM module to reinitialize the failure rate model.

MODEL OUTPUTS

The outputs of the simulation are maintenance logs and statistics that characterize the operations and performance of the given sector. These outputs have been chosen to provide fine-grain analysis of a particular maintenance concept. Thus, any inadequacy in maintenance operational performance will be pin-pointed by the outputs. The log outputs consist of maintenance event (PM and CM) logs, facility logs and technician time critical workload. The statistical outputs are composed of performance parameters and relevant statistical distributions.

The PM and CM logs detail the maintenance history of each event over the simulation period. They contain detailed information such as the time the maintenance event occurred, the particular technician summoned and his response time, and the time it took to travel and to perform maintenance duty. For a CM event, the log also contains restoration time and logistics delay time.

The facility log provides a summary of CM and PM maintenance performance at each facility in the sector. For each facility, the log tabulates the number of outages, average restoration time, facility availability, the number of PM performed and cancelled if it is not performed within a specified time limit.

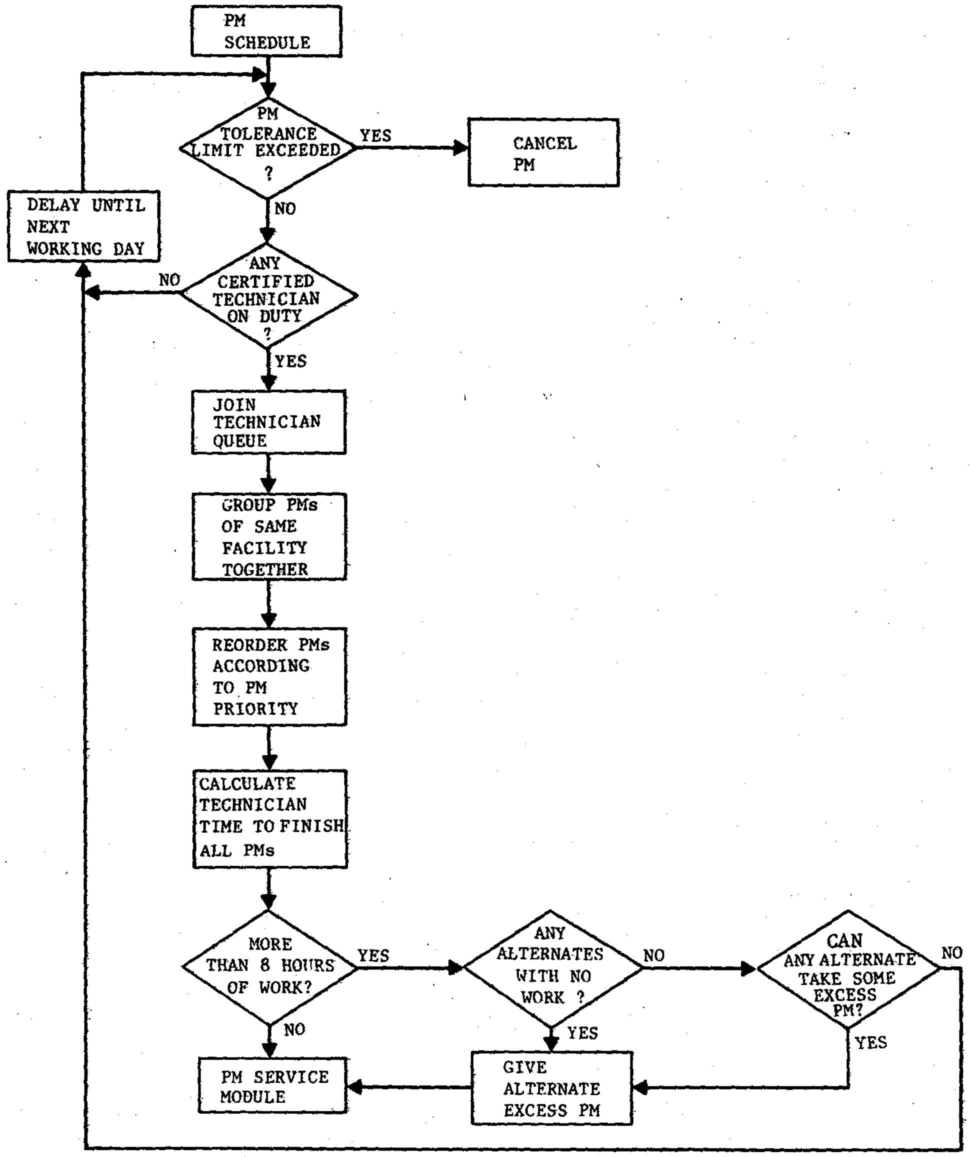

FIGURE 3
EXAMPLE OF PM TECHNICIAN ASSIGNMENT LOGIC

The time critical workload log details the amount of time a technician consumed in performing maintenance actions (PM and CM) and the associated travel time. This output is used to evaluate the impact of a maintenance strategy on each technician's workload.

The log outputs described above are essentially record-keeping on the individual event or facility or technician basis. The statistical outputs are concerned with overall sector maintenance performance parameters and statistical distributions. The sector performance parameters include average technician time critical workload, average restoration time, total performed PMs and cancelled PMs. The statistical distributions are histograms outputted by the model on such parameters as restoration time and CM waiting time.

VALIDATION OF THE SIMULATION MODEL

To ensure the developed simulation model conforms with the actual maintenance operations and procedures of the modeled sector, a validation procedure was conducted using data collected from the field. The data collection time frame was chosen to be eight weeks so that sufficient number of facility outages could be recorded.

The model validation is divided into two phases, as shown in Figure 4. Phase I is concerned mainly with the validation of the model's technician selection logic. The PM and CM

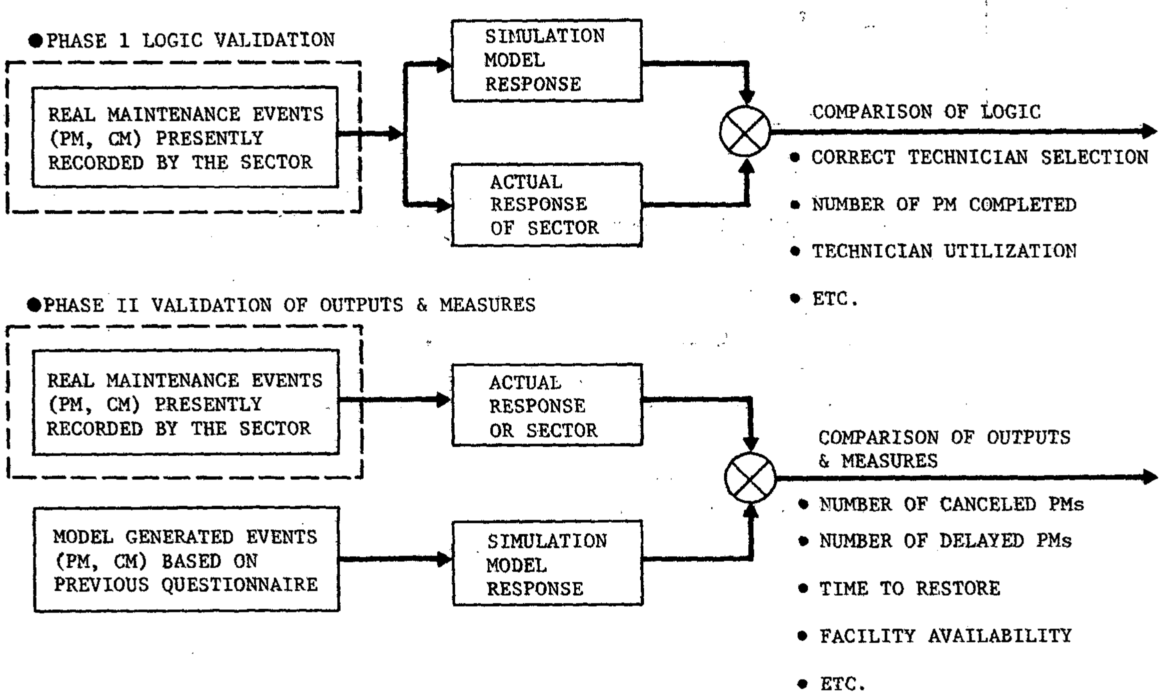

FIGURE 4
VALIDATION APPROACH

events recorded in the sector during the validation data period are used as input to the model. The sector's recorded actual decision as to which technician is assigned the PM or CM task is compared to the model's decision on the event-by-event basis. The end result is a score sheet of the number of times the model logic has selected the technicians correctly. Phase II deals with the validation of the outputs and measures of maintenance performance, such as the number of cancelled PMs, number of callbacks, time to restore, etc. In the actual sector, the outputs and measures are compiled based on the correspondingly recorded validation data. The model's maintenance parameters are automatically produced at the end of the simulation run.

Aside from the difference in the objective of the two phases, another major difference that can be observed, in Figure 4, is the inputs of maintenance events to the sector model. Phase I uses the actual PM and CM events, recorded in the sector, as inputs to the model. In Phase II, the model generates its own PM and CM events based on the sector data base.

The result of the Phase I validation indicated that the model's logic of technician selection for a given PM (one-man and multi-man) or CM event matched almost exactly to the recorded technician assignment. An added check was made to the model during Phase I by comparing the performance parameters such as time critical technician workload between the model and the actual sector. It was shown that comparison was quite accurate.

For the Phase II validation, the initial time of a 48 week interval was randomly selected and then this time interval (approximately one year) was partitioned into 6 time periods which defined the simulation periods of the 6 independnt computer runs. The relevant maintenance parameters from the outputs of each of these runs were compared with the corresponding ones computed from the recorded data. The result of the comparison is given in Table 1. This table indicated that no significant differences were observed for parameters such as total number of completed PMs, cancelled PMs, average time to restore, and number of equipment outages for all the six runs. One minor difference was observed in the validation. It can be noted from Table 1 that the actual number of leave days for the technican in the sector during the validation time period is higher than that of the model. This is becase of the seasonal dependency characteristics of the technician's annual leaves. Since the validation data was taken during the summer, more leaves were recorded. The model was subsequently modified to schedule more leaves during the summer season.

Overall, it can be concluded that the model has been validated. Therefore, the model can be used as an effective baseline for evaluating advanced maintenance concepts.

TABLE 1

VALIDATION OF OUTPUTS AND MEASURES

	ACTUAL	RUN I	RUN II	RUN III	RUN IV	RUN V	RUN VI
NO. OF PM	515	485	505	494	494	490	509
NO. OF CANCELLED PM	0	4	5	7	3	8	99
NO. OF UNSCHED. PM	86	101	99	101	99	75	93
NO. OF OUTAGES (ELECTRONIC)	21	25	25	27	23	24	27
NO. OF OUTAGES (OTHER)	13	26	25	24	22	26	24
NO. OF CALLBACKS	26	27	29	19	22	22	29
AVG. TIME TO RESTORE (HR.)	2.2	2.29	2.35	1.96	2.35	2.36	2.75
AVG. TIME CRIT. WORKLOAD (%)	43.7	44.7	48.7	46.3	45.3	53.0	49.0
NO. OF LEAVE DAYS	15.3	4	3	4	5	3	3

APPLICATON OF MODEL

The simulation model was applied to evaluate alternative organizational concepts for the maintenance of modernized NAV/COM (navigation/communication) facilities for a typical sector. It was assumed that only the NAV/COM facilities would be replaced with solid-state technology with RMM and the rest of the non-NAV/COM facilities in the sector would remain unchanged. Thus, the sector contained a mixture of solid-state and vacuum-tube technology equipments, representing an example of a transition period.

The sector selected for the evaluation of the alternative organizational concepts contained 44 electronics and 7 environmental technicians servicing the 107 facilities. The geographical distribution of the technicians is shown in Figure 5. It can be seen from this figure that the sector organization was decentralized since the technicians operated from 9 work-stations (SFO/SFOU). Each work station was responsible for its nearby facilities. The inherent advantage of the decentralized organization is the quick response to repair facility outages.

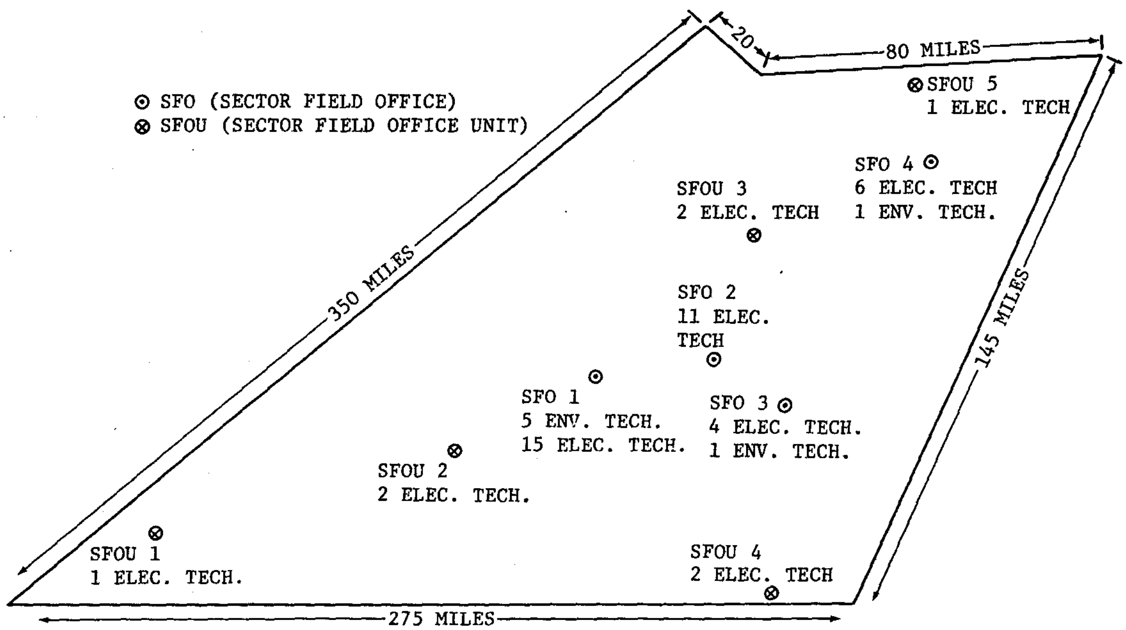

FIGURE 5
GEOGRAPHICAL DISTRIBUTION OF SECTOR'S TECHNICIANS

The combined features of solid-state technology and RMM for the NAV/COM facilities should reduce significantly the intensive number of technician trips required for the baseline system. Therefore, the question arises as to whether there is an alternative to the baseline maintenance organization which could be more efficient with respect to maximizing the benefits of decreased technician visits to facilities.

A more centralized organization is an alternative to the baseline decentralized organization for the maintenance of the modernized NAV/COM facilities. Under the assumed centralized organizational structure, the maintenance of the solid-state NAV/COM facilities is performed mainly by a group of electronic technicians dedicated to these facilities. Some of the potential benefits of the centralized organization include higher technician productivity and savings in training cost and logistics cost. However, the operational feasibility of this organizational concept is constrained by the acceptable time to restore facility outages and technician workload expended in the additional travel time.

The decentralized and centralized organizational scenarios for the maintenance of the modernized NAV/COM facilities were evaluated by the simulation model to assess their operational feasibility. The results of the simulation studies are shown in Table 2. The relevant set of measures of maintenance productivity and performance used in this analysis are shown in the first column of this table. The second column of this table shows the values extracted from the simulation of the baseline sector organization and equipment technology. The next two columns are from the simulation of the two organizational scenarios involving the hypothetical implementation of solid-state NAV/COM equipments and RMM. In the centralized scenario (last column), the dedicated NAV/COM technicians operate from two main work stations, SFOU 2 and SFO 3 of Figure 5.

TABLE 2

COMPARISON OF MAINTENANCE ORGANIZATIONAL PERFORMANCE OVER ONE SIMULATED YEAR

MEASURE OF PRODUCTIVITY AND PERFORMANCE	BASELINE (PRESENT)	SOLID-STATE NAV/COM PLUS RMM	
		DECENT.	2 PT. CENT.
NO. OF TECH. REQUIRED	24	15	15
NO. OF CERTIFIED NAV/ COM TECH.	20	14	5
AVG. TIME CRITICAL TECH. WORKLOAD (%)	45	44	46
AVG. NO. OF MISSED PMs PER NAV/COM FAC.	2.2	< 1	< 1
AVG. TIME TO RESTORE NAV/COM FAC.	2.7 HRS.	1.9 HRS.	3.0 HRS.
AVG. NO. OF CALLBACKS PER NAV/COM TECH.	7.0	10.2	15.5

To determine the operational feasibility of the scenarios, the corresponding values under the scenario columns are compared with those under the baseline case, on a row-by-row basis. For a scenario to be viable, the performance and productivity values from the scenarios should be comparable to those of the baseline. The first two rows specify the number of required electronic technicians and the number of these technicians with NAV/COM certifications. They serve as inputs to the simulations. It can be seen from the first row of Table 2 that the introduction of solid-state NAV/COM and RMM provides a savings of 9 technicians. The second row indicates that there is substantial savings in training cost since only 5 dedicated NAV/COM technicians are required. The average time critical workload for the technicians is an important parameter. It can be observed from Table 2 that the average time critical workload is approximately the same before and after the implementation of the new concept, all within 1% of the baseline.

The next two entries in this table are the average number of missed PMs per facility for the NAV/COM and the non-NAV/COM facilities, respectively. These two measures pertain to the sufficiency of staffing. Table 2 reveals that the average number of missed PMs per facility is not significant relative to the baseline.

The average time to restore NAV/COM facilities in the scenarios is approximately within that of the baseline. It can be noted that the centralized scenario takes approximately 1 hour longer in restoration time. This is due to the increased travel time in the centralized scenario. With respect to non-NAV/COM facilities, negligible difference in average time to restore exists between the scenarios and the baseline.

The last entry in Table 2 focuses on the average number of callbacks responded to by a NAV/COM technician. This row shows a large variation. This large variation can be explained by the variation in the number of certified NAV/COM technicians in the scenarios (row 2). As the number of technicians with NAV/COM certification is reduced drastically, such as in the centralized organizational structure, the number of callback events per technician increases since the outage rate remains the same.

In summary, since the pertinent outputs produced by the simulations of the scenarios generally appear to be comparable to those of the baseline, it can be concluded that the two organizational scenarios appear to be operationally feasible. The main tradeoff for the final selection is reduced restoration time for the decentralized organization versus reduced training requirements for the centralized organization.

CONCLUSION

This paper has presented a description of a dynamic simulation model of a maintenance organization. In esence, this model simulates the maintenance-related events, technician maintenance activities, and procedures of a given sector on the day-to-day basis. This model has been validated by a field experiment. Hence, this model can be utilized to evaluate the operational feasibility of new maintenance concepts with confidence. An illustration of the applicability of tis model is also provided in this paper.

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